# Mountain Pine Beetle Detection and Monitoring: Phase II Enhancement, Interpretation and Evaluation of Airborne Imagery

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### Introduction

This report outlines particulars regarding the second phase of a pilot study to acquire, process and evaluate digitally converted aerial photographic imagery for the detection and monitoring of mountain pine beetle (MPB) infestations. This project was jointly funded by the BC Ministry of Forests, West Fraser Mills Ltd. and Forestry Investment Innovation. Without this research support this project would not have been possible and the authors gratefully acknowledge this support.

The overall study developed and refined an applied remote sensing strategy for resource management by the MOF, West Fraser and the SFU/FII research team. It involves monitoring and control of MPB infestations. This project addresses the most efficient and reliable remote sensing strategy for investigating the possibility of identifying and mapping early infestation stages (current attack) of mountain pine beetle in lodgepole pine forests in a practical and cost effective manner. In addition the project will recommend optimum strategies for identifying and mapping advanced MPB attacks (red and gray attacks).

An additional aspect of the study is to evaluate applied RS tools for the general monitoring and control of forest pathogens and pests as well as related procedures that can be used for other environmental monitoring practices: e.g. riparian vegetation, erosion, logging practices, suspended sediment concentrations, stream morphology and habitat.

This research evaluation and remote sensing study was planned to specifically enhance knowledge by identifying and evaluating the remote sensing imaging systems and analytical procedures that most accurately and cost effectively address this critical MPB problem. This study will provide a strategic framework with short, medium and long-term considerations of the role of remote sensing in forest resource management.

## Previous Research

Over the past decade MOF has engaged in a series of research projects to evaluate the potential for orbital and airborne electronic sensor systems to contribute to forest health resource management. Although substantial financial and personnel resources have been committed to these projects. The results have been generally inconclusive at best and often clearly disappointing.

Satellite imagery suffers from: (1) availability problems due to cloud cover and orbital periodicity, and (2) inadequate spatial resolution for forest health issues that require a suitable spectral image for individual tree crowns.

The use of airborne imaging spectrometers (e.g. CASI) and multispectral scanners (e.g. GERS) has proved disappointing. There have been no satisfactory results for reliable early (current attack) detection of MPB and other forest pests. Secondly these airborne line-imaging systems

are not good mapping instruments in comparison with aerial photography. This inevitably drives up the costs for any operational project.

An obvious gap in remote sensing research, related to these forest health problems, has been the almost complete lack of experimentation (and comparison) with digitally converted colour, colour infrared and multispectral aerial photography. In particular it is recommended that all experimental studies be evaluated against this standard in terms of: (i) mapping accuracy, (ii) potential for automated spectral interpretations and (iii) cost effectiveness. Aerial photography is the "gold standard" in terms of mapping.

Of concern is the continuing assertions by the contractors, undertaking MOF MPB remote sensing projects over several years of testing, that their results were "promising" and indicated "operational potential". This is further outlined by the "positive spin" that has been placed on apparently unreliable results evaluated in some of these reports. The results, in contrast, clearly indicate that no reliable remote sensing signal for predicting early current MPB attack under the tested conditions has been detected.

Related to this concern is the fact that the scientific "particulars" were often not available for evaluation: specifically with many CASI studies there was no adequate information, throughout the sequence of experiments over the past few years, regarding the: (i) spectral image bands used, (ii) analytical procedures and (iii) statistical verification. At no point was adequate information made available by the contracting companies in order to permit scientific validation of the conclusions presented in their reports.

Additionally, the processed imagery used in many of the analyses was not made available in order to permit independent examination and evaluation. All of this could have been done without violation of "proprietary" agreements in contracts.

If predictive classifications are tested in the future, future operational trials should include rigorous trial designs and utilize rigorous and independent blind testing. All scientific and analytical procedures should be made available for independent evaluation. All imagery used in the analyses should be made available for independent examination and evaluation.

### STRATEGIC PLAN

The current MPB infestation has provided an urgent incentive to address a strategic plan for remote sensing of forest health in British Columbia. Although this proposed plan directly addresses the present MPB problem, most aspects relate to other forest health problems. It is considered to be a template for future investigations into the suitability of using remote sensing for a specific problem (MPB) and the development of cost effective operational procedures. Three important criteria must be met in order for this plan to be effective: Under all circumstances the suitability for knowledge transfer from research studies to operational conditions must be considered. Of equal importance is the cost effectiveness of the procedure and the degree that it can be implemented in a business environment involving private competition. Finally, of paramount importance is the need for a "patent" treatment of all investigative research.

#### Short Term Strategy

The current provincial visual overview flight program should evaluate the utility of incorporating an increased use of aerial photography for detection and mapping of "red attacked" trees. It should be a point of evaluation to determine if this will be less expensive and/or more comprehensive. In addition to detection and mapping there is considerable potential for objectively and comprehensively monitoring the spread of this infestation by mapping the red attack and/or, for the late spring early summer months, mapping the spreading current attack.

For general forestry applications conventional aerial photography should be used as much as possible. For forest health issues the use of digitally converted colour and colour infrared aerial photography is recommended for detection and mapping of forest health conditions that require the capability to clearly distinguish individual tree crowns. In circumstances where it is desirable to have greater spectral detail (e.g. for early detection of forest health problems) the use of a multispectral photographic camera system (4 spectral bands: b, g, r & nir) or twin camera system (colour and infrared film in two synchronized cameras: b, g, r & nir) and digital image conversion is recommended.

For large area evaluations, that do not require the ability to resolve individual tree crowns, a variety of satellite imagery can also be considered.

# Medium Term Strategy

The continuation of a suitable aerial photography program to meet the BC forest health needs in terms of recurrent mapping for infestation detection and spread is essential. The development of a computer assisted spectral image interpretation and mapping procedure, using the digital aerial photography, becomes the next logical step. Investigation into the suitability of using colour infrared and/or multispectral aerial photography for current attack detection of MPB infestations and other forest health early-detection applications should be undertaken.

# Long Term Strategy

Long-term considerations involve the melding of an operational digital aerial photography detection and mapping program with an experimental program. The experimental program should utilize airborne & orbital platforms and electro optical systems (digital frame cameras and imaging spectrometers) in support of the "operational" digital photography. This should not be considered as a primary investigative technology until the utility is clearly demonstrated. An important aspect will be to monitor and evaluate the need, at some time in the future, to phase out the use of aerial photography and replace that operational program with new generation direct digital frame or line imaging electro optical systems.

## REMOTE SENSING EVALUATIONS

Mountain pine beetle (Dendroctonus ponderosae Hopkins) is one of the most serious forest insect pests native to British Columbia. In British Columbia this beetle attacks and kills standing, large diameter lodgepole pine (Pinus contorta var. Latifolia) trees. Lodgepole pine forests make up 35% of British Columbia's forested land base and account for approximately 30% of the total timber volumes harvested in British Columbia. Mountain pine beetle attacks are common due to large areas of mature or over-mature lodgepole pine stands which are a result of successful forest fire suppression. Recent epidemic outbreaks have, on average, resulted in the death of over 30 million mature pine trees per year. Currently a state of emergency exists in BC as a result of the increasing spread of MPB in BC's forests.

There is a large body of forestry related remote sensing research in the academic literature (e.g. in the *International Journal of Remote Sensing* this has accounted for approximately 10% of the studies). Most of these studies have involved the use of orbital imagery to undertake small-scale (large area) analyses. In comparison, very few studies involving airborne data have been published (<1%).

In British Columbia over the past decade there has been a sequence of studies investigating the utility of orbital and airborne electro optical remote sensing related to forestry health.

Even though there has been an intensive interest and considerable funds have been spent in research, there have been no studies that have been able to reliably detect current attack from mountain pine beetle in lodgepole pine. The few current attack studies undertaken often have conflicting "promising" results that subsequently are not confirmed by further research. Many studies have not provided adequate information to permit scientific validation of their results and, on a number of occasions, have provided inadequate information regarding basic procedures and spectral data.

With the detection of red attack the remote sensing results were surprisingly poor in many cases. Although colour aerial photography can routinely image red attack there was often significant errors with both orbital and airborne (CASI) imagery. In general, with satisfactory spatial resolution, most systems could have a reasonable level of success with detecting red attack. There were no discussions of costbenefit considerations for these studies but clearly aerial photography would be quite favourable.

#### Imagery

The evaluated remote sensing data in this research study included: digitally converted multispectral aerial photography providing normal colour, colour infrared and two groups of false colour infrared composite images; digitally converted colour negative aerial photography; digitally converted colour infrared aerial photography; digitally converted black & white infrared aerial photography; combined 6 band colour and colour infrared imagery, and; combined 4 band colour and B&W infrared imagery.

# Imagery acquisition

Site-specific MPB infestation imagery was flown on April 3, May 15, June 3, June 12, June 13, August 14, October 11 and October 16, 2002. Imagery was acquired at scales of 1:8000 and 1:16000. In addition a series of imaging flights were undertaken to test film exposures, filter combinations and twin camera synchronized colour and near infrared imagery. These imaging flights occurred on February 20, March 2, March 17, May 16, June 12, June 13, June 14, August 14, August 15, October 15, October 17, October 24, and November 1, 2002. Figure 1 shows one of the



JEPPESEN FliteMap



Figure 1: Digital aerial navigation chart showing imaging flight lines over Marilla area sites on June 3, 2002.



Figure 2: Schematic "map" of the SFU Remote Sensing FTP site containing all project imagery.

65 flight line maps that were generated for each site showing the specific location imaged. All flight line maps are posted on our FTP site. A total of 21 imaging flights, producing 476 test images, 3611 MPB infestation images and 832 forestry habitat images, were undertaken. All

flight line maps and imagery are posted on the SFU Remote Sensing FTP site: 142.58.173.39 (ID: anonymous; password: email address of user; note: use only binary transfer for imagery). Figure 2 shows one of the FTP site "maps" indicating the structure of the site and location of the images. These FTP "site maps" are also posted on the FTP site.



Figure 3: Four band multispectral image of Deerhorn site, August 14, 2002. Image 1: blue; Image 2: green; Image 3: red; Image 4: nir.

Each multispectral image (Figure 3) contains four spectral bands (near infrared (NIR), red, green and blue) that were combined digitally into 4 colour composites: (Figure 4) normal colour, colour infrared and two false colour infrared images for visual and computer analysis and classification. The twin camera imagery consisted of two images: (Figure 5) colour with colour infrared and colour with B&W infrared. These data were digitally converted and evaluated to determine varying levels of interpretational utility and spatial resolution performance for forestry health parameters. In addition the colour and false colour digitally converted aerial images were used as a comparative baseline to assist with the performance evaluation of the multispectral imagery.



Figure 4b: An enlarged area from Figure 4a. Red attack trees are red on RGB & RIRB and green on IRRG & IRRB. TL:RGB; TR:IRRG; LL:IRRB; LR:RIRB.



Figure 5a: Twin camera colour composite multispectral imagery: Deerhorn site, October 16, 2002.TL:RGB; TR:IRRG; LL:IRRB; LR:RIRB.



Figure 5b: An enlarged area from Figure 5a. Red attack trees are red on RGB & RIRB and green on IRRG & IRRB. TL:RGB; TR:IRRG; LL:IRRB; LR:RIRB.

## Imagery Registration

Both the multispectral and twin camera imagery required registration of each individual image to a single image. For the multispectral imagery the NIR, red and blue images were registered to the green image. With the twin camera imagery the infrared imagery (colour IR and B&W IR) was registered to the normal colour imagery. This cross-image spectral band registration created sets of 4 band and 6 band multispectral imagery for enhancement, interpretation and classification. In all instances one of the images was left unaltered to permit precision photogrammetric mapping.

A second group of images were registered across time (same site from different imaging dates) to permit forward and backward evaluation of colour changes in MPB infested trees. This registration resulted in large "single" image files containing up to 33 separate images across the period from April to October, 2002.

Imagery registration is a somewhat time consuming activity requiring approximately one hour per image. Cross time images take substantially longer as image rotation and scaling issues complicate the registration: assuming that the multiband (4 and 6 band) images making up these data sets are already registered, a single cross time image will take one to two man weeks. All image registration was undertaken at SFU in the SFU Remote Sensing Laboratory using ER Mapper image processing software.

### Imagery Evaluation

Six areas of mountain pine beetle (MPB) infestation, to the west and southwest of Prince George, were sequentially imaged by the SFU Remote Sensing Laboratory between April and October, 2002. These sites were established by MOF as test sites for the evaluation of experimental remote sensing systems and procedures. The extent of MPB current attack was mapped, by field survey at the individual tree level, in the fall and winter of 2001 and the fall of 2002 (see Appendix A). All indicated trees are numerically keyed to data tables (see for example Table A1). A total of six sites were ground truthed by MOF and SFU/MOF combined. The total number of trees examined was 2890.

There was an apparent change in most of these currently infested trees at these six sites over the 2002 season (a small percentage of these 2001 infested trees had still shown no visible change by November 2002). On our April 3, 2002 imagery, the previous year's dead trees were clearly visible as red standing dead trees. The 2001 ground truthed current beetle attack was not detectable by visual examination on any of this early April imagery. On the later May 15<sup>th</sup> and June 3<sup>rd</sup>, 12<sup>th</sup> and 13<sup>th</sup> imagery, the currently infested trees increasingly became visible through colour changes on the various composite multispectral images.

By August 14<sup>th</sup> most of the 2001 attacked trees had changed from a green to red colour. This continued through the fall such that by October a larger percentage of the previously infested trees had continued changing colour to red. The August (and later) imagery then became another form of "ground truth" (verification data) such that we could trace back to trees that were green in April from trees that had changed to red by August. This colour shift showed these trees had died and we worked back through the June and May imagery to determine the earliest detectible "signal". Appendix B contains a sample from a small area of a registered time sequence from one of these six sites. These visible changes were most pronounced on the infrared false colour composites but were also detectible on the normal colour composites to a lesser degree. The colour changes are the result of reflectance changes on the trees in both the visible and near infrared spectral regions. Our results clearly indicate that early detection of "current" MPB infestations is possible.

# RESULTS

Aerial imagery was acquired at two different imaging scales (1:8000, and 1:16000) for six different MPB research sites and eight different imagery test sites. The MPB sites were imaged from April 4<sup>th</sup> to October 16<sup>th</sup>, 2002 using 4 and 6 band multispectral imaging systems.

Image Processing: The acquired aerial photography was developed in Vancouver (B&W photography), Calgary (colour infrared photography) and Dayton, Ohio (colour and colour infrared photography). Imagery was developed and scanned throughout the study period with the film being developed as soon as possible following exposure to minimize deterioration. The digital film conversion (scanning) was undertaken in Vancouver by three separate companies: McElhanney, Triathalon and Silver Sands. Scanning resolution varied for test purposes however the B&W imagery was scanned at 12, 16 and 18 microns and the colour imagery was scanned at 18, 20 and 21 microns.

Image quality is generally excellent, although the colour infrared imagery processed in Ohio was not test processed, as a result it was underdeveloped producing a darker than normal image. The generally excellent quality of the imagery includes film exposure, developing and digital conversion. Colour enhancements and spectral combinations are adjustable and the imagery can be custom enhanced to assist with the interpretation of the different environmental parameters. Although some understory areas could not be imaged in direct sun due to vegetation overhang most of the selected sites have been imaged with good sun illumination.

Specific objectives set for the analytical phase of this study indicated that the following needed to be determined more precisely:

## Spectral Parameters

The spectral parameters examined were limited by the spectral sensitivity of the films used and the spectral transmission of the various filters. Generally we used "broad band" imaging in the blue, green, red and near infrared.

The B&W film (Agfa 200 PE 1) used with 301a infrared cut-off for the visible bands and specific numbered Kodak Wratten filters produced the following broad spectral bands:

blue (47 + 301a: 400nm - 500nm) green (40 + 301a: 475nm - 580nm) red (24 + 301a: 580nm - 680nm) nir (89b: 680nm - 740nm).

The colour negative film (Agfa N400) produced the following broad spectral bands:

blue (400nm - 475nm) green (525nm - 580nm) red (600nm - 660nm).

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The false colour infrared film (Kodak 2443 & 1443), used with a 520nm
yellow filter, produced the following broad spectral bands:
    green (520nm - 580nm)
    red (625nm - 675nm)
    nir (620nm - 850nm).
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The B&W film (Agfa 200 PE 1) used with a 600nm red filter produced the following broad spectral band: nir (600nm - 740nm).

The colour film was used in conjunction with the two nir sensitive films to produce a 4 or 6 band multispectral image using a twin mapping camera configuration.

Our results from the 2002 imaging indicate that: (1) the multispectral camera produced more distinct separation of reds and current attack than did the twin camera package; (2) the false colour combination of nir, red and blue provided the best visual separation of trees for mapping both red attack and spring current attack (see Appendix B). Both the nir and blue spectral bands improved visual mapping and classification in comparison with the other spectral combinations (rgb & irrg).

# Timing of Onset

Seasonal "timing" of the onset of visibly detectable current attack (when the first spectral alterations become clearly visible) on this imagery varied between our six sites. At the Blackwater and Marilla sites we had clearly detectible evidence of current attack by May 15<sup>th</sup> at the Nazko site we did not obtain distinct separation until June 3<sup>rd</sup>. Taken as a whole it is safe to say that a spreading current attack is clearly visible by late May early June. Further analyses and refinement with more comprehensive imaging, seasonal and environmental data may enable earlier reliable detection (ca. early to mid May). Although some changes in specific trees could be detected on some of the April 3<sup>rd</sup> imagery there is no indication that this can be considered reliable.

### Image Processing

Analytical procedures to enhance and objectively identify "red attack" and spreading infestations ("current attack") consist of preprocessing, visual interpretation and classification. Preprocessing is potentially the most complicated as it involves enhancements during image scanning, histogram trimming and viewing enhancements and image modification to improve classifications. During the scanning process we had little control over enhancements. With our contractors who provided this service we established a procedure that altered the image as little as possible. In general default manufacture recommended settings were used without any additional contrast enhancement. Our preference was for a simple linear transform but due to the logarithmic nature of the image density a straight linear conversion did not provide adequate analog to digital conversion. Although we obtained very good quality image scans this is an area that requires further investigation to determine optimum procedures for digital conversion of film products to be used in multispectral digital image processing.

### Reliability

With red attack trees we can clearly detect and map all trees that have changed colour to red. In this sense the reliability (detection accuracy) is close to 100%. With digital image classification this is

slightly reduced since some of the reds are shaded and are classified as shade areas. This is very minor and percent success remains around 99%. The issue becomes more complicated when the reliability addresses successful detection of all trees that were attacked in the previous year. Most of the heavily attacked trees (75 - 100% attack in our ground truth classification) can be reliably detected in August at the red attack stage. However many of the less heavily attacked trees (<50% attack in 2001) did not change colour by August and a number had still not changed colour in the fall (November). These trees were not detectible and if included as a statistical component would cause the detection reliability to vary considerable from location to location depending upon degree of attack and other undetermined factors.



Figure 6a: August 14, 2002. Four sub-images from the Blackwater multispectral imagery:

Top Left - IRRB false colour infrared composite with new red attack trees as green, healthy trees as pink and orange and old reds as blue; Top Right - results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red; Bottom Left - normal colour infrared composite with heavily attacked trees ground truthed in 2001 circled & numbered, new red attack trees as red, healthy trees as green and old reds as grey; Bottom Right - normal colour infrared composite with new red attack trees as red, healthy trees ground truthed in 2001 circled & numbered, healthy trees as green and old reds as grey.



Figure 6b: June 12, 2002 & August 14, 2002. Two sub-images with supervised classifications from the Blackwater multispectral imagery:

Top Left - June 12: IRRB false colour infrared composite with new reds as yellow, healthy trees as pink/orange and old reds as blue; Top Right - June 12: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red; Bottom Left - Aug. 14: IRRB false colour infrared composite with new reds as green, healthy trees as pink/orange and old reds as blue; Bottom Right - Aug. 14: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red.

For this reason our reliability concerns dealt primarily with attacked trees that died and turned red by August. While we are aware that more trees will have changed in September and October, problems with aspen birch and other deciduous trees undergoing senescence altered clear detection of reds as attacked pine.

Our evaluations of the detection of current attack on our June, May and April imagery were based completely upon heavily (75 - 100%) attacked trees in 2001. As a result we had generally reliable detection of these trees in June and May both visually and through image processing classification procedures (see Figure 6).

# Cost Effectiveness

Evaluation of the cost effective aspects of these procedures is partially constrained by the fact that we did not commercially contract our imagery acquisition, registration and processing. Within the university environment return on capital investment (equipment costs etc.), profit and job security were not a budgetary issue. Our expenses were constrained by the immediate operating and personnel costs. This of course considerably reduces the expense of conducting this type of research and the acquisition and processing costs. However, there is little doubt that aerial photography is substantially less expensive than any other airborne imaging systems. The increased resolution and generally interpretative utility of aerial photography provides data detail, mapping accuracy and imaging flexibility that is not available with orbital sensors.

## Knowledge Transfer

Central to this type of resource management is the determination of an effective and reliable procedure that can be implemented through competitive bidding by private sector companies. There is little applied utility if it is not practical to implement the findings of this research to assist with management of this acute forest health problem. For this reason we have initiated experiments in imaging with a twin mapping camera setup to simulate our multispectral imaging system (see Figure 5). Although this was only undertaken very late in the imaging season we have results that show satisfactory comparative results and reasonable confidence that integrated multispectral RGB & NIR imaging can be undertaken by many photo survey companies. This will permit knowledge and procedural transfer in a competitive context that can be operational more or less immediately.

# CONCLUSIONS

Within the context of this study, airborne remote sensing of forest environments for forest health determinations (MPB) is most suitably undertaken using multispectral aerial photography at scales of 1:8000 for early detection of current MPB attack and 1:16000 for mapping and sequential monitoring of red and grey attack.

From an "operational" perspective, the use of a twin mapping-camera setup with colour and B&W infrared film will provide the best approximation of the multispectral imagery with near comparable performance in a competitive private sector context (open bidding). The most suitable scales for contracted imagery would be optimized in terms of cost and performance by using 1:10000 imagery for early detection of current attack and 1:20000 for red attack mapping and monitoring.

Digital conversion of aerial photography for MPB detection and monitoring should be undertaken at 16 to 20 microns for B&W imagery and 18 to 24 microns for colour and colour infrared imagery. Image enhancements should not be added to any of this imagery in the scanning process. All enhancements should be undertaken as second-generation imagery such that they can be removed or modified.

This study has developed and recommended an operational remote sensing strategy for BC involving MPB as well as other forest pathogens, pests and environmental problems. This includes:

 optimum strategies for identifying and mapping advanced Mountain Pine Beetle attacks (current and red attacks);
 an evaluation of RS strategies involving other forest health considerations;
 a strategy for the most efficient and reliable remote sensing investigation of the possibility for identifying and mapping early infestation stages (current attack) of mountain pine beetle in lodgepole pine forests;
 potential for extrapolation of these early detection strategies to other forest health applications, and; 5. a determination of the operational capability, cost effective performance and knowledge transfer potential in resource management for the remote sensing procedures evaluated.

This study has critically considered traditional and new remote sensing tools and methods for the control of forest pathogens and pests as well as related procedures that can be used for other environmental monitoring practices: e.g. riparian vegetation, erosion, logging practices, suspended sediment concentrations, stream morphology and habitat.

This research evaluation and remote sensing study was planned to specifically enhance and transfer knowledge by identifying and evaluating the remote sensing imaging systems and analytical procedures that will most accurately and cost effectively address the current critical mountain pine beetle problem. It has provided a strategic framework with short, medium and long-term considerations of the role of remote sensing in forest resource management.

### Appendix A

Ground truth trees displayed on remote sensing images for four of our six sites. All images are normal colour composites and all trees examined and marked in the field have their crowns circled and numbered. These numbers are keyed to appropriate tables (e.g. see Table A1).



Ground truthed trees at the Blackwater site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.



Ground truthed trees at the Marilla 2M13 site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.



Ground truthed trees at the Nazko site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.



Ground truthed trees at Nechako Canyon site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.



Table A1: Ground truth data for the first 23 trees from the Blackwater site. A total of 614 trees were ground truthed at this site.

# Appendix B

Sample MPB detection and monitoring imagery for the Blackwater Site, 2002. Imagery taken with International Imaging Systems multispectral camera using 89b (NIR), 25 (R), 46 (B) and 57 (G) filters and Agfa 200 PE 1 extended red film scanned at 16 microns. All imagery was flown at 1:8000. Normal colour (R G B) and false colour (NIR R G) are shown for each date. Note that on the false colour images the healthy trees appear red and the attacked trees appear as fading to green or green.



April 3, normal colour: snow on ground, old reds attack in upper left.



April 3, false colour: snow on ground, old reds attack in upper left.



May 15, normal colour: old red attack upper left, fading current attack.



May 15, false colour: old reds are green upper left, current attack trees are yellow.



June 3, normal colour; upper left: old reds; current attack are fading & yellowing.



June 3, false colour; upper left: old reds (green-blue); current attack are yellow.



June 12, normal colour; upper left: old reds; current attack are fading & yellowing.



June 12, false colour; upper left: old reds (blue); current attack are yellow-green.



August 14, normal colour; upper left: old reds; current attack are red, fading & yellowing.



August 14, false colour; upper left: old reds (blue); current attack (bright green & yellow).